EXTINCT NUCLIDES — "MUCH ADO ABOUT NOTHING"

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A concise review of the status of research on short-lived nuclei is presented. The importance of these nuclei is very great in spite of the fact that they are essentially absent today (except for cosmic ray products). The significance of these nuclei for understanding broader cosmic problems is outlined and it is shown that they are a key to the earliest processes in solar system formation and possibly provide a link with presolar processes in the interstellar medium or of intense activity of the early sun.

A few reminiscences are about some random interactions with Hans Suess are given illustrating different ways of doing and thinking science.

Some time, about 0.000000035 AE ago, a tall man with a wild but full head of hair was riding together with me in an elevator in the Institute for Nuclear Studies at the University of Chicago. I believe we were both going down, not up. This person began muttering something to me that seemed obscure but could have been important. He knew that I was then trying (at the instigation of Harold Urey) to measure rare gases in stone meteorites. My chore was to do the abundance and isotopic composition of Ne, Ar, Kr and Xe and the K content of chondrites. For some reason, Urey believed that it would be useful to date meteorites using the decay of ^{40}K to ^{40}A (now ^{40}Ar). I had added the other noble gases to be independent. The wild appearing individual was (or so I was later told) a most innovative and interesting scientist with lots of ideas. He often looked as if his hair was arranged by a high voltage discharge. It was Hans Suess — he murmured — "^{129}I". "What was that?" I asked in response to this opening gambit of conversation in the descending elevator. "^{129}I" he repeated — "you should look at it, it could be important!" Then he lumbered rapidly out of the elevator to go provoke or confuse some other poor soul (see Suess, 1949; Suess and Brown, 1951). Having recently inherited his "high vacuum" line in the Jones laboratory and seen how an expert really works — pinholes, Glyptal and all, it seemed to me that if this was important, it must be an easy victory. Surely, I could blow glass better than that. That first laboratory which Urey had assigned me, Hans Suess' old stall, had just been used for trying to date tektites (Suess *et al.*, 1951). This was my first exposure to natural green bottle glass. The choice of the problem still has its effects on me, as my colleagues and I are working actively on tektites today (Shaw and Wasserburg, 1982; Ngo *et al.*, 1985). The samples are just very much smaller, the problem is still profound. Many years and many isotopes later I discovered that blowing glass and building high vacuum systems and getting precise numbers was only a part of the game and guessing about the possibilities and deeper realities of nature was another part of the game.

It was this elevated suggestion that prompted R.J. Hayden and me to do the first measurements of Xe in meteorites to look for ^{129}I decay (Wasserburg and Hayden, 1955) and obtained a lower limit of 4×10^8 y for the time interval between nucleogenesis and the formation of meteorites. We used to speak of nucleogenesis back then because of Big Bang and George Gamow (1946) and α, β, γ (Alpher *et al.*, 1948). This was before the major shift to the evolutionary point of view of Burbidge *et al.* (1957) which changed from Big Bang creation to one of long term galactic nucleosynthesis. It was Willy Fowler who insisted that I give up genesis and be converted to synthesis (c.f. Wasserburg *et al.*, 1960). Now we have advanced to some of this (for low z elements) and some of that (for the rest). Most of the elements in which I am interested are from that. These negative results on ^{129}I were the basis for several great review papers (by other authors) on short-lived nuclei for which no evidence had been found. As no one but the Noddacks (Ida Noddack and Walter Noddack, 1934) had ever tried to measure I in meteorites at that time we had to use their data. (There was not even any good K determination on meteorites then, really just measurements of blanks from K rich "analytical grade" reagents.) Confirmation of our negative result on ^{129}Xe by Reynolds and Lipson (1957) on another poorly chosen sample led us all to believe that extinct most likely meant absent. This abyss of ignorance was followed by the discovery by John Reynolds of excess ^{129}Xe in the meteorite Richardton (1960) which showed a clear sign of the presence of at least one presently extinct nuclide, ^{129}I.

Hans Suess and I grew somewhat closer, so that he could, after a while feel free to call me at dinner time in our "new" apartment (the old Craig apartment over the coal bin) just after Naomi and I got married. "There should be some formula for such and such" he announced over the phone, "can you help me with this, I am not so good with mathematics and you are so clever at it." A big shot scientist calling a humble (not so humble?) student for help. What a challenge! I said that it was worth a try. On returning to the dinner table with my wife I began to scribble on several paper napkins. This did not help my digestion, or my new marriage, but then . . . by the end of dinner it was all figured out. I called Hans up on the phone and told him the formula (it had something to do with the abundance curve and nuclear systematics). "Thank you, Jerry" he said, "that looks right, but I am sorry I won't be able to acknowledge you in my paper because I originally got Hans Jensen to do this some time ago but forgot the answer, good nite." For this and other reasons, Hans only had dinner at our house once after that time.

Suess was famous for just getting an apparatus to work at the most marginal level but producing excellent results. The use of paper clips to tie electrical leads together in very sensitive counting equipment could drive Meyer Rubin and maintenance people mad. No one dared touch anything, a clip could fall off or be rattled loose and ruin everything! Then no more data! I never learned this trick and am condemned to build solid, long-lasting equipment to which I am forever wedded.

The spirit of science in solving nature's mysteries and the carriers of wisdom are mysterious. Hans has always (almost always) been such a carrier. He once appeared in my lab at Caltech (around 1960) and said "Helium." We were sitting by a new rare mass spectrometer (HeNeArKrXe) that I had just built and installed. "What about helium?" I inquired. "Oh," says Hans, "it should be stored in the ocean bottom by flowing in from the bottom. *Maybe* it has a different isotopic composition. You should do it." "Well, *maybe*," said I, "but the machine does not have the right detectors, and I would have to rebuild the flight tube. Why don't you talk to Al Nier, he could do it, but it is hard to believe that I should devote all my efforts to that now. Aldrich and Nier (1948) probably have all the answers anyway." There is something about messages; it takes someone to receive them. Well that should explain my failures.

I have had the privilege of knowing some raspy voiced individuals, two from Austria and the other from Russia (all with bottles, two with high pitched voices and one with card tricks) during that time period between 1948 and the late 50s. Maybe the voice and the mystery go together.

The comments outlined above are prologue and the material outlined below is a summary of all of what I think we currently know about the mystery of extinct and near extinct nuclei this many years later.

SUMMARY AND DISCUSSION

^{244}Pu was alive and well in the early solar system. The abundance of this nuclide at 4.6 AE is not precisely fixed but is in the neighborhood of ^{244}Pu/^{238}U $\approx 10^{-2}$. I have chosen the value of 7×10^{-3} from Hudson *et al.* (1984) (see Table 1). The presence of ^{247}Cm has not been detected but an upper limit to its abundance is ^{247}Cm/^{235}U $\leq 4 \times 10^{-3}$. Both ^{244}Pu and ^{247}Cm are only produced by ''r'' process nucleosynthesis. The stellar site where this takes place is not established but must involve very high temperatures and neutron densities. From the limits on ^{247}Cm and the presence of ^{244}Pu it follows that the last substantial addition of real ''r'' process nuclei took place somewhere between about 10^8 y and 5×10^8 y prior to solar system formation. Obviously this could have taken place in either discrete events or continuously. The time scale for the last substantial ''r'' process contribution to the solar system appears fixed by these data. (We note that no results on the presence of superheavy elements has been found to stand either experimental testing or theoretical scrutiny.) The preponderence of the U and Th in the solar system must have been produced much before this time of late ''r'' process addition ($\sim$ 4.7 - 5.1 AE). From the precisely established ages of some solar system objects at 4.555 AE, the ^{235}U/^{238}U ratio at that time and the estimated relative production rate of 1.5, a firm lower limit to the age of the universe is 6.4 AE. This yields an upper limit for the Hubble constant of 100 km/sec/megaparsec using the standard $\tau H = 2/3$ relation. Various models of galactic nucleosynthesis can fit a $\sim$ 10 AE time scale quite well but there are no nuclear chronometers yet identified which *require* this or greater times. The extent to which the astronomical observations and theoretical considerations of stellar and galactic evolution and of globular clusters may require a much greater time is not decided (Flannery and Johnson, 1982).

The nuclei ^{26}Al, ^{107}Pd and ^{129}I were all present in the early solar system. The abundance of these species relative to a nearby isotope of the same element are all in the neighborhood of 2×10^{-5} to 10^{-4} (see Table 1). The fact that they are in roughly comparable abundance in spite of the wide range of mean lives (1.1 to 23 my) must mean that they were produced in events closely related temporally (i.e. over a very short time scale). Their low abundance is thus not due to a large interval of decay without production which would decrease the abundance of each species i by $e^{-\lambda_i \Delta}$. Rather, they were the result of adding freshly synthesized matter (about 10^{-4} of the nuclear species) to old material. The time scale for this last gasp addition to solar system matter is between 10^6 to 9×10^6 y, with the higher value being a maximum. The usual explanation of the presence of ^{26}Al is shown in the cartoon in Figure 1. This is the original figure shown by T. Lee in an early presentation. The general view is that an association of rapidly evolving stars in a cloud injects freshly synthesized material from either supernova or nova explosions into the surrounding cloud medium. This material (a mixture of old and freshly formed nuclei) then condenses to form the solar system on a $\sim$ 1 my time scale.

Table 1

Nuclide	Solar system abundance at ≈ 4.6 AE	
^{41}Ca	^{40}Ca/^{41}Ca	$\leq (8 \pm 4) \times 10^{-9}$
^{26}Al	^{26}Al/^{27}Al	$\approx 5.0 \times 10^{-5}$
^{107}Pd	^{107}Pd/^{108}Pd	$\approx 2.0 \times 10^{-5}$
^{129}I	^{129}I/^{127}I	$\approx 1.0 \times 10^{-4}$
^{146}Sm ?	^{146}Sm/^{144}Sm	$\sim$ 0.012; 0.005
^{247}Cm	^{247}Cm/^{235}U	$\leq 5 \times 10^{-3}$
^{244}Pu	^{244}Pu/^{238}U	$\approx 7 \times 10^{-3}$
	^{235}U/^{238}U	= 0.33

This time scale is about a factor of 20 to 180 less than was obtained by just considering ^{129}I alone. With regard to ^{129}I, it is quite reasonable to consider that some of the ^{129}I represents matter produced over a longer time scale and some was a late addition with the other shorter-lived nuclei. The proportion of the ^{129}I that was old is difficult to estimate but could be from 10 to 90% of the total. The mechanism of production of ^{26}Al is distinct from ^{107}Pd and ^{129}I. Production of the former is from proton reactions while the production of the latter must involve (single) neutron capture by Pd and Te or else multiple neutron capture in a mini-"r" process. From the abundances measured and the time scale indicated, all of these nuclei must have been produced in a completely different and smaller event than the pure "r" process nucleus ^{244}Pu. The older ^{244}Pu contribution to the then ambient medium was far greater than this late injection of ^{26}Al, ^{107}Pd and ^{129}I, etc.

The upper limit recently obtained for ^{41}Ca shows that, if this nuclide was produced, it must have been produced greater than 1.8×10^6 y prior to the formation of the solar system. If we assume all of the short-lived nuclei were produced at essentially the same time, then the last gasp injection took place somewhere between 1.8×10^6 y and a maximum of 9×10^6 y prior to solar system formation.

The most direct inference from all of the preceding considerations is that the sun condensed from a medium that contained recently ejected nucleosynthetic debris at a modest level of concentration. This debris came from distinctive sites of stellar nucleosynthesis and was reasonably (not perfectly!) mixed on a 10^6 y time scale. As the above nuclei have been identified in different solar system objects, they appear to tie certain solar system events to late injection. The ^{26}Al effects have so far only been found in material *associated* with early solar nebular condensation (see Grossman [1980] for the proposed origins and formation of Calcium-Aluminum rich inclusions). ^{129}I was present both in these materials and possibly in small planets. The ^{107}Pd is present in iron meteorites which must have formed in differentiating planets. A general scheme outlining the above chronology is shown in Figure 2. If we assume all of the short-lived nuclei were originally present prior to solar system formation, then relative to the time of last nucleosynthesis we obtain the chronology shown. If the precursor medium had ^{26}Al/^{27}Al $= 10^{-3}$, then the total time to form the CaAl rich inclusions which contained ^{26}Al was 3×10^6 y. To produce and melt small planets which contained ^{107}Pd as a radioactive nuclide would require planet accumulation on a time scale not much greater than the mean life. From the measurements of the ages of meteorites and the ages determined for the earliest differentiation of the earth and moon a time gap of 5×10^7 to 10^8 years is known to exist. These time scales are commensurate with the accumulation times of cm-100 m, km and

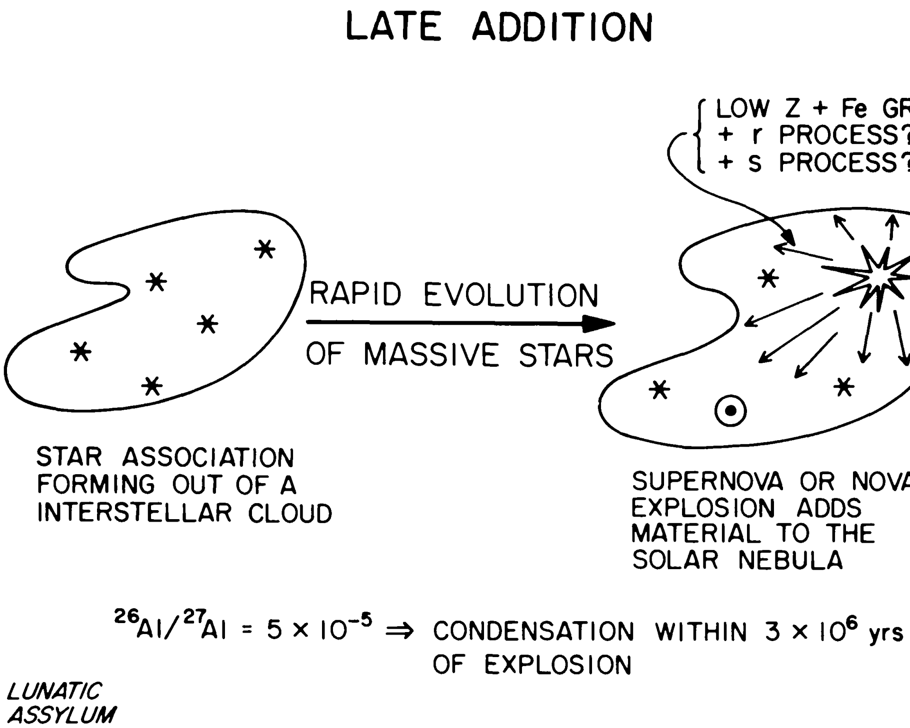

Fig. 1 Model of late addition of ^{26}Al and other short-lived nuclei. This model associates solar system formation with regions of a molecular cloud containing rapidly evolving massive stars (novae, supernovae, or other stellar sources) which are injecting freshly synthesized material into the cloud. The protosolar nebula is considered to have resulted from a local collapse in this region, ultimately forming the sun and solar system. The cloud contains matter from very ancient sources and a small amount (10^{-4}) of freshly synthesized material including ^{26}Al. The possible sources of ^{26}Al (novae, red giants) appear reasonably well defined. However, the production of ^{107}Pd and ^{129}I requires neutrons from a different stellar source. This model connects the solar system time scale with stellar processes in a cloud. Other nuclei are also ejected into the medium and are then to be preserved in grains to provide the isotopic heterogeneities presently found in the solar system (after Lee *et al.*, 1976a, b).

10^3 km planetary bodies as calculated by Safranov (1969) and Ward and Goldreich (1973). If the time scales for coalescing the protosolar system from the precursor medium is estimated from the free fall time ($\tau_{ff} = 4 \times 10^7/\sqrt{n_H}$) and taking the time scale to be given by the lifetime of ^{26}Al ($\bar{\tau}_{^{26}Al} \sim 1.0 \times 10^6$ y) this implies a hydrogen density n_H of $\sim 2 \times 10^3$ H_2/cm^3 for the initial state. This is quite compatible with the densities in a molecular cloud. The whole process of collapse and aggregation appears to be compatible within the mythologies shared by cosmochemistry and astrophysics. There seems to be a most immediate connection between the solar system and the interstellar medium at the time of formation.

The presence of ^{26}Al in the abundance found above applied throughout the whole solar system would provide an ample heat source for melting small planets formed within a few million years. This problem was first identified by H.C. Urey (1955). If ^{26}Al was the heat source for melting small planets, some evidence should be preserved in these bodies if they were cooled on a time scale comparable with ~ 1-2 my. To find this evidence we must have *very* old planetary objects. So far, *no clear evidence of ^{26}Al has yet been found in planetary objects to prove that this was the source of heating*. The objects which are produced by planetary differentiation ("basaltic achondrites") that caused Urey to propose the ^{26}Al heat source so far show no evidence of ^{26}Al (Schramm *et al.*, 1970). The oldest object yet dated directly is the meteorite Angra Dos Reis whose age is 4.555±0.005 AE (see Jacobsen and Wasserburg, 1984 and Wasserburg *et al.*, 1977 and references therein). This is the best precision (2σ) in age determination so far achieved using long-lived radioactivities. Angra Dos Reis is a cumulate igneous rock which must have formed on a planet and thus should be somewhat younger than the early formed objects we would want. In principle it is possible to use one of the short-lived nuclei themselves to provide a very precise chronometer since one can measure ^{26}Mg*/^{27}Al or ^{129}Xe*/^{127}I to within a few percent. This would allow us to place objects in a self-consistent time scale which was very precise (10^5 y for ^{26}Al and 10^6 y for ^{129}I). However, this requires that the freshly synthesized nuclei be well homogenized in solar system matter in order to have an initial reference state as pointed out by Cameron (1973). From the available data for both systems this does not appear to be the case. Some efforts to establish such chronology have been made for ^{129}I but they remain subject to this problem (Podosek, 1978). A sensible experiment might be to obtain both the absolute age and evidence for ^{26}Al on various meteorites. One problem is that of finding planetary materials with high enough Al/Mg (10^3-10^4) in order to observe any effect. There is also enormous difficulty in establishing absolute ages with the precision required (better than 5 my in 4,600 my) in order *a priori* to select the correct old sample. It is more likely that the problem may be solved by a hunt and search of plausible candidate meteorites.

Having laid out the basic observations and canonical inferences, it is of merit (i.e. provocative) to consider some problems and alternatives. The model of a single (or closely connected) nucleosynthetic event(s) to explain the abundances of the short-lived nuclei is most plausible. That this happened before solar system formation is however not required. We cannot yet place the meteorites and their constituent parts in an absolute chronometric scale measured back from today with adequate precision. The arguments associating the refractory inclusions in Allende with early solar condensates are reasonable (see Grossman, 1980) but are not unequivocal as a chronometer or as proof of the actual processes. Indeed there are many conflicts between a condensation model for a hot part of the solar nebula and the mineral phases observed in so called refractory (and sometimes volatile rich) inclusions. Material has certainly been subject to complex

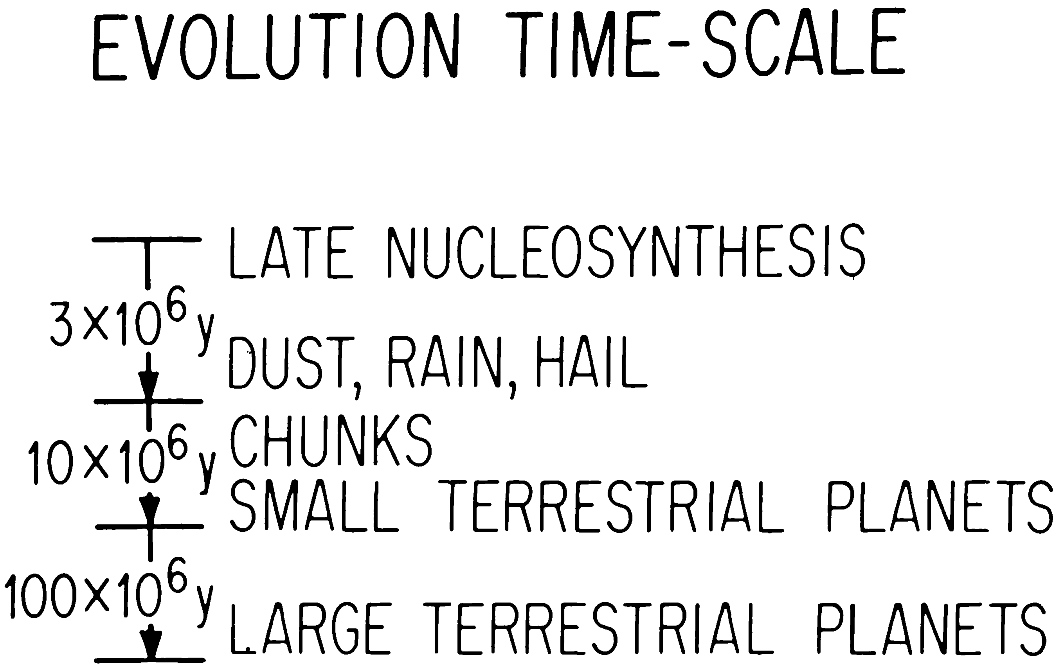

Fig. 2 **Evolutionary time scale for the solar system assuming the model of Figure 1 (after Wasserburg and Papanastassiou, 1982). The starting time is from the production of ^{26}Al in stellar sources within the molecular cloud. In order to preserve the ^{26}Al in small objects like CAIs would then require a time of $\sim 3 \times 10^6$ y between the original stellar production and the formation of droplets of molten material which become isotopically homogeneous and crystallized phases with ^{26}Al/^{24}Mg in different proportions yielding the ^{26}Al-^{26}Mg isochrons observed in many samples. The presence of ^{107}Pd in iron meteorites requires that the time scale be about 10×10^6 y in order to preserve this relatively short-lived nucleus in planetary differentiates. The time scale of 100×10^6 y comes from the observed difference in ages between the earth, moon and meteorites and is in agreement with the theoretical work of Safronov (1969) and Ward and Goldreich (1973).**

reprocessing and it is not possible to relate a given object to a well defined evolution. It is not clear from purely theoretical considerations as to how much of the solar nebula was hot. The heating was probably very restricted in space and time and it is not obvious how to relate the meteorites and planets which we study to the medium from which we think they came. Some recent attempts to tie the complex chemical evolution together with infall and circulation dynamics around the protosun has been made by Morfill (1983). This is an important area requiring further study and closer ties between mineral chemistry and "cooking" either by the sun or in planets (cf. Meeker *et al.*, 1983). Secondly, while the ratio of short-lived/stable and exotic/stable nuclei appears to be $\sim 10^{-4}$ (excluding oxygen!), this observation only pertains to condensed materials directly associated with the terrestrial planets. This may or may not be attributable to the whole solar system including the sun.

If the results are representative of the solar system, this requires the injection of $M_{FRESH} \sim 10^{-4} M_\odot$. This presumably occurred at the same time at which the general isotopic anomalies for many elements not associated with short-lived nuclei were introduced. Whether the injecting sources (e.g. supernova, nova) are a trigger or simply a coincidence is a matter of debate (see Truran and Cameron, 1978 and Cameron and Truran, 1977). It is difficult to assign causal phenomenon for our particular star in a stellar nursery. In terms of the precursor state prior to condensation of the sun, ^{26}Al (if it were in high abundance) would yield a major source of ionizing radiation in the interstellar medium (Consolmagno and Jokipii, 1978). If the isotopic results are not representative of the bulk solar system (and thus $<< 10^{-4}M_{\odot}$), then they could indicate either injection into the placental ISM or production within the proto- or early solar system (see Figure 3). The basic question is whether these effects are due to pre- or post-solar system processes. The time scale implied by ^{26}Al is substantially less than the time for one solar mass to evolve onto the main sequence. As a result it is of primary importance to assess the effects of early solar evolution on the residual matter surrounding the sun.

While local irradiation of a solar mass to produce ^{26}Al is excluded due to ionization loss (Lee, 1978), it is possible that the radioactive nuclei could have been produced by irradiation of a dust cloud or of planetary surfaces. A schematic diagram showing a local irradiation by the sun at sufficient proton energy to product ^{26}Al is presented in Figure 3. If the sun went through a T-Tauri phase with a luminosity of $10^4L_{\odot}$ it is plausible to expect extreme temperatures within 1 AU (causing surface heating and evaporation) and an energetic solar cosmic ray fluence of 10^{21} to 10^{22} p/cm^2 (E $\gtrsim$ 30 MEV). This corresponds to a flux about 10^5 to 10^6 times greater than the current solar cosmic ray flux for a period of $\sim 3 \times 10^6$ y. Although some workers do not believe the sun could have gone through a T-Tauri phase (A.G.W. Cameron, personal communication) there is a very high probability that it could have been an x-ray star. While this would not provide much flash heating at 1 AU, the high energetic particle flux could produce many nuclear reactions. This type of model has not been intensively investigated. While ^{26}Al would certainly be produced in such a scenario, it is not evident that sufficient production of ^{107}Pd and ^{129}I from secondary neutrons would take place. However, this has been suggested to explain the extrapolated initial value of $(^{107}Ag/^{109}Ag) = 0$ for the IVB meteorites. Such a model would produce short-lived nuclei rather late, after some small planetary objects formed. The problems of isotopic heterogeneity of both ^{26}Al and of the stable nuclei of several elements might be more easily explained by ''local'' solar system processes. The absence of ^{26}Al in some samples that have been interpreted as early solar condensates or droplets must in any case require gross heterogeneity in ^{26}Al distribution (Esat *et al.*, 1978; Hutcheon, 1982; Hinton and Bischoff, 1984). A reconsideration of the scenario by Fowler *et al.* (1962) with less extreme conditions and more modest expectations is warranted. Some low Z elements are Big Bang and do not have to be made late, thus the fluence level required is much more modest. A local irradiation model must include the irradiation of dust and small planetary bodies. It is not clear that icy bodies are required for neutron scattering a la FGH for the nuclei under consideration.

The preceding comments are not meant to deny the plausible interpretation of a direct and immediate connection with the ISM and stellar nucleosynthesis. However, since the first clear indications of short-lived nuclei were found, it has always been evident that in principle there were two alternative scenarios (see Figs. 1 and 3). This must be kept in mind while we are exploring to find the true solution to the problem. No self-consistent theory has yet been proposed that adequately explains the key isotopic, chemical and mineralogic observations.

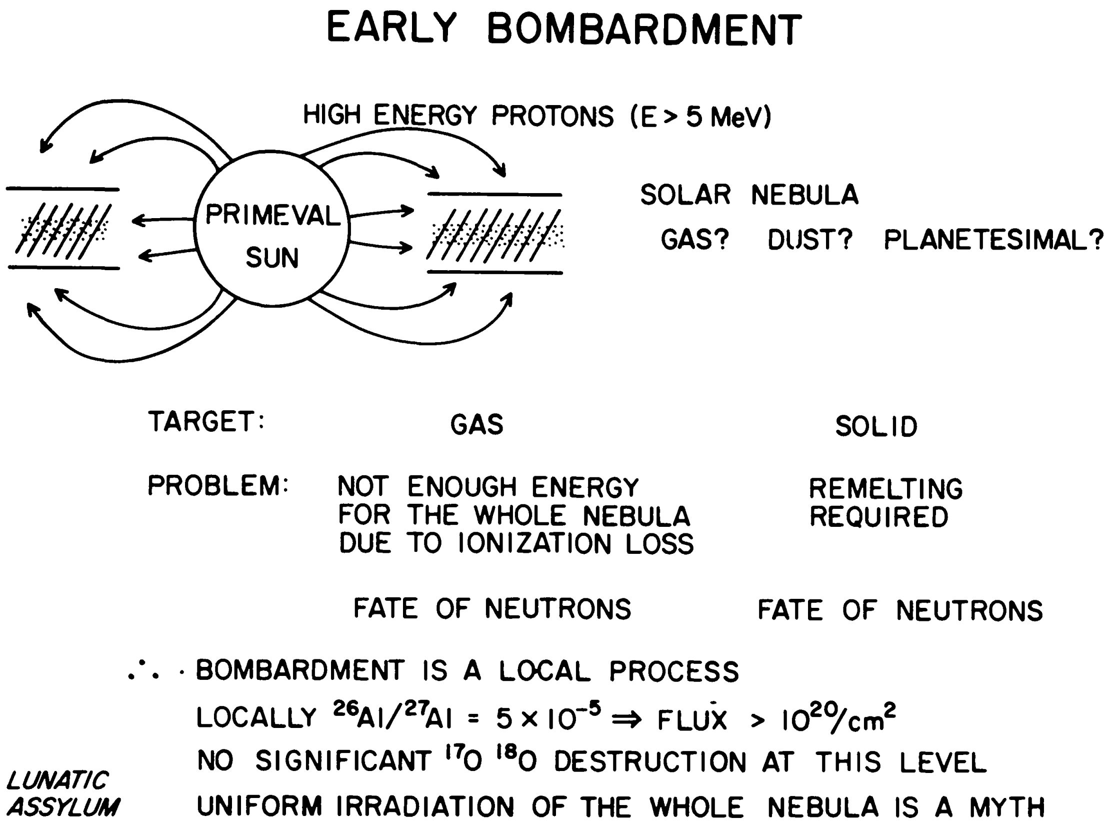

Fig. 3 An alternative model which considers the sun to have gone through a stage of very high activity (T-Tauri or x-ray star stage). In this model it is clear that the proto-sun cannot produce $^{26}Al/^{27}Al \sim 10^{-5}$ by energetic proton bombardment for the uniform irradiation of one solar mass of material due to the presence of H and He (Lee, 1978). Therefore, to produce ^{26}Al in the abundance indicated, this requires that the gas be largely dissipated and that the bombardment take place on dust (possibly with some small amount of gas), small "rocks," or on the surfaces of small planetisimals. This mechanism can readily produce ^{26}Al at the appropriate level, however, the production of ^{107}Pd and ^{129}I requires neutrons and no complete calculation of this model has been made. This model implies that the isotopic anomalies are modifications of solar material and are not due to addition. Indeed many of the general anomalies may not be nuclear at all but due to unspecified complex photo-chemical reactions. It is possible with irradiation and heating of solids (evaporation) that the environment for producing CAIs is in fact rather oxidizing and not governed by H_2. In this model the time scale is tied to the time of solar activity and the state of matter in the solar system (possibly after planetisimals have formed). This is in sharp distinction to the model in Figure 1. The matter is not yet decided, however, many workers prefer evolution in a molecular cloud.

While alternatives require study, the recent exciting report of ^{26}Al as a source in the galaxy certainly appears to support the view that the sources for the solar system came from the ISM and not local production. The study by Mahoney *et al.* (1982) has reported the possible presence of a 1.808 MEV γ line as a diffuse (?) source in the galaxy. A more extensive analysis of this complex data set by Mahoney *et al.* (1984) shows a well defined signal for ^{26}Al. The signal is there but it is not strong compared to spacecraft background. The most recent analyses of the HEAO 3 data identify this γ-ray line as due to the decay of ^{26}Al, resulting from the transition of ^{26}Mg from the first excited state to the ground state. Further measurements of this γ flux will be required to decrease the background and improve the counting statistics and to more firmly define the nature and distribution of the sources. These workers have estimated $^{26}Al/^{27}Al \sim 10^{-5}$ for the galaxy which is remarkably close to the abundance found for the early solar system. A recent discussion of the HEAO results is given by D. Clayton (1984). The result by Mahoney *et al.* (1984) is most exciting and would appear to eliminate supernova sources (which are relatively rare) because of the high ^{26}Al abundance (about four solar masses of ^{26}Al in the galaxy). From the observations on meteorites, it should be noted that SN as a source of ^{26}Al, were never very plausible because of the low $^{26}Al/^{27}Al$ ratio for the average ejected matter. In order to provide the ^{26}Al observed in meteorites from a SN source it was necessary to assume that the ^{26}Al came from the matter in a special zone in the supernova with very high ^{26}Al yield. With no dilution from the ISM and for a "standard" supernova production ratio of $(^{26}Al/^{27}Al)_{SN} \sim 10^{-3}$, this would require that $\sim 5\%$ of all the ^{27}Al in the solar system was from a single late event (see Table 2, Woosley and Weaver, 1982; and see Rodney and Rolfs [1982] for a discussion of the Al-Mg cycle). This was a view which my colleagues and I have always felt was most unreasonable. Other proposals and recent experimental studies showed that red giants could produce $^{26}Al/^{27}Al \sim 1$ which then eliminates the problem of adding too much fresh material at the last event (Arnould *et al.*, 1980; Nϕrgaard, 1980; Champagne *et al.*, 1983a, b, c). Further, other studies have concluded that novas would readily produce ^{26}Al. However, none of the mechanisms listed above would produce ^{107}Pd in an obvious fashion as this requires neutrons ($<\sigma\phi\tau> \sim 10^{-4}$).

In a steady state within a dense cloud in which fresh injection is taking place uniformly we would expect the abundance of a short-lived nuclide to be proportional to the mean life. The abundance of ^{107}Pd and ^{26}Al should also be quite different if they were in steady state in a molecular cloud. This does not appear to be the case for the three nuclides under discussion. As a result it seems the ^{107}Pd (and possibly the ^{26}Al) must have been produced rather locally within the ISM.

Insofar as a dense molecular cloud was the placental site from which the matter of the sun was derived, it is necessary that this medium contain rapidly evolving stars ejecting material. From present considerations it is believed that molecular clouds were isolated from the general ISM and galactic nucleosynthesis for $\sim 10^8$ y. This is compatible with the ^{244}Pu and ^{247}Cm results where these nuclei are produced during galactic nucleosynthesis far before the formation of the molecular cloud that appears to have been the medium from which the sun formed. Some of the ^{129}I could be from the pre-cloud source. However, the short-lived nuclei would have to be produced within the cloud and require rapidly evolving stars that disperse fresh products into the medium which are rapidly separated and condensed on a time scale of $\sim 10^6$ y.

With regard to further searches for other extinct nuclides it appears that ^{53}Mn is a prime target as the life time is in the correct range. A very tempting problem would be to look for the decay products of technetium isotopes. This element is known to be present in stars and may provide the best identification of the nature of one of the stellar sources since the production mechanisms have been studied. The recent revision of the mean life of ^{60}Fe (Kutschera *et al.*, 1984) suggests a search for $^{60}Ni^*$. The absence of γ lines associated with ^{60}Fe and its daughters (Mahoney *et al.*, 1983, 1984) and the presence of ^{26}Al as a diffuse source may also have a larger astrophysical significance with the longer mean life for ^{60}Fe. The lines associated with ^{60}Fe would then surely have been observed if they were produced along with ^{26}Al. The absence of γ lines from ^{60}Fe might imply that supernova injections on a galactic scale were much more frequent in early times than at present or that Fe production is completely separated from ^{26}Al production and comes from some stages preceding molecular cloud formation.

In restricting our attention to relatively long-lived nuclides ($\gtrsim 10^6$ y) it must not be forgotten that some isotopic anomalies present in solar system material suggest radioactive progenitors with much shorter lifetimes. Demonstration of the presence of almost pure ^{22}Ne (Ne-E) in solar system material (see Figure 20) by Black (1972) suggested the presence of dust grains of interstellar origin containing trapped presolar system materials. Clayton (1975b) suggested that freshly synthesized ^{22}Na ($\bar{\tau}$ = 3.6 y) trapped in dust grains was the source of this anomaly. This explanation would require the separation of stellar debris on an almost instantaneous time scale and the preservation (or trapping) of the noble gas daughter for the trip from another star to make meteorites in the solar system (Black, 1972; Eberhardt, 1974; Eberhardt *et al.*, 1979, 1981). Some theoretical analyses of possible stellar production mechanisms and the trapping of Ne-E have been carried out (c.f. D.D. Clayton, 1975a, b, 1979; and Arnould and Nørgaard, 1978). It could mean preservation of rapidly condensed grains around some precursor stars or local production by the early sun. In either case, the trapping mechanism for noble gases is quite obscure at the present time. The puzzle of short-lived nuclei and the formation of stars is certainly not quite put together.

In addition, it is important to note that the general isotopic heterogeneities found within the solar system (which so far include Ne, O, Mg, Ca, Ti, V, Kr, Sr, Ba, Sm, Nd) are, as yet, unexplained. The isotopic effects are correlated between different elements in only very few cases. Most usually they appear unrelated. The amount of exotic oxygen of Clayton *et al.* (1973) is much higher ($\sim \times 10^2$) than that of other nuclides and it is difficult to store it in many separate reservoirs. If the CAI are indeed condensates from a hot gas then the oxygen in them (^{16}O enriched) would reasonably represent the solar value (dust + gas) and not just the dust. The general anomalies are not directly and obviously related to the presence of short-lived nuclei nor the processes which we think make them. There is no coherent physical-chemical model that ties together these observations with starting materials of gas and dust from the interstellar medium or of dust, planets and some gas. Indeed it is possible that some of the anomalies are not due to nuclear processes, but rather reflect unknown or ignored mechanisms operating in the early solar system operating during or even after the first planetary accretion processes. Many inclusions that are called high temperature condensates appear to be evaporative residues (c.f. Kurat *et al.*, 1975). The scale of isotopic heterogeneity in the solar system is not obviously compatible with the larger astronomical scales of heterogeneity in clouds, particularly when these are only gas and dust as distinct phases (c.f. Wasserburg and Papanastassiou, 1982). In addition to the isotopic problems, there is some question as to the nature of the processes which formed the calcium-aluminum rich inclusions (CAIs). While some workers originally considered them to be condensates from a hot parcel of nebular gas, this no longer seems to be accepted. The CAIs have a bulk chemical affinity with an equilibrium condensation model, but there are substantial difficulties in relating the mineralogy and paragenesis to such a model. Some strong evidence exists for crystallization from melt droplets, some for a type of back reaction (involving normal oxygen and then later with halogens and other volatiles), and finally there is evidence for metamorphism and replacement. Coupled with these problems, it appears that the clusters of refractory-rich elements found in CAIs as "nuggets" and "fremdlinge" (Wark and Lovering, 1978; Palme and Wlotzka, 1976; El Goresy *et al.*, 1977) are of normal (not exotic) isotopic composition and have a complex formation history involving an oxygen-rich environment and a reducing environment at very different temperatures. As the fremdlinge appear to be strange refractory-rich solar system objects (not exotic) that were formed and subsequently included in the CAIs, it follows that there was extensive physical and chemical processing and segregation within the nebula before the CAIs were formed (Armstrong *et al.*, 1985a, b; Hutcheon *et al.*, 1985). Perhaps the CAIs are secondary objects formed from aggregates of dusty refractory-rich material that was then flash heated (large impacts, solar heating). It is my current view that processes in the early solar system will play a dominant role in explaining the general isotopic anomalies and some of the short-lived nuclides. Hints of non-nuclear schemes are found in experiments like those of Sander *et al.* (1977); Thiemens and Heidenreich (1983); Arrhenius *et al.* (1979) (for a theoretical analysis, see Navon and Wasserburg, 1985). In fact, the isotopic observations are a reflection of processes — not of a place! We cannot readily assign each isotope to a special stellar source and store it (without mixing) only to be called up when it has to be added to the particular meteorite grain with the anomalies. The turbulent and violent activity in the neighborhood of forming stars and solar systems will undoubtedly require more insight. Perhaps what is needed are more elevator rides with wild haired people who can better sniff the winds of formation — and pass on obscure but valuable suggestions to the random passengers.

This short note is a summary of a more extensive review to be published in *Protostars and Planets* (1985). It is intended to provide a summary of my report at the Suess Fest in La Jolla and of my regard for a long-time colleague and friend.

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